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The objectives of the research efforts supported by this DURIP award are to demonstrate and characterize the operation of optical coherent transient procesing and true-time-delay devices at bandwidth well in excess of a gigahertz. The mode-locked Ti:Sapphire regenerative laser amplifier, associated pump laser combined with our existing, chirped laser system, and support equipment purchased with the DURIP funds has given us the capability to demonstrate and evaluate of coherent transient processing and true-time-delay devices in the 1-100 GHz bandwidth regime. Research in this operating regime is crucial to the development of high performance rf photonic systems critical to our national defense.

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Final Technical Report

on

Optical Coherent Transient Processors and True-Time-Delays

Grant Number

F49620-98-1-0277

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Abstract

Real-time, wide band information storage and signal processing devices are critical to many military and commercial systems in order to perform complex functions such as *pattern and target recognition, secure communications, network routing, tactical database management, and phased array radar.* Optical coherent transient technology has the potential to perform real-time storage and signal processing at data rates up to a terahertz, with storage/pattern densities on the order of a terabit per centimeter squared, and with data block sizes/time-bandwidth products well over 10000.

Two key issues in the operation of large broadband antenna arrays are efficient management of the inherent complexity of these systems and efficient implementation of controllable, broadband true-time-delays. Optical coherent transient technology has the capability of efficiently imposing true-time-delays up to several microseconds on signals with bandwidths in excess of 100 GHz. These attributes, combined with the added advantage that 1) these delays are controllably programmable, 2) that over 10^5 delays can be programmed in a cubic centimeter of material, and 3) that phase and amplitude sensitive processing and delay can be performed simultaneously, make coherent transient true-time delay an extremely promising technology for future radar systems.

The objectives of the research efforts supported by this DURIP award are to demonstrate and characterize the operation of optical coherent transient processing and true-time-delay devices at bandwidth well in excess of a gigahertz. The mode-locked Ti:Sapphire regenerative laser amplifier, associated pump laser combined with our existing, chirped laser system, and support equipment purchased with the DURIP funds has given us the capability to demonstrate and evaluate of coherent transient processing and true-time-delay devices in the 1-100 GHz bandwidth regime. Research in this operating regime is crucial to the development of high performance rf photonic systems critical to our national defense.

Equipment Purchased

The following list identifies the name, manufacturer, and associated costs for all the equipment acquired under DURIP Grant F49620-98-1-0277

Item	Name	Manufacturer	Cost
1	Mode-locked laser w/regen	Clark-MXR	$33,381.12
2	Millenia Pump laser	Spectra-Physics	$47,061.81
3	Solid Etalon	Mellles Griot	$2,700.00
4	Power Meter	Molectron	$1,505.77
5	Beam Analyzer	Merchantek	$4,180.35
6	Spatial Filter	Newport	$1,062.00
7	Variable Beamsplitter System	CVI Laser Corp	$1,312.95
8	AO Modulator Set	Isomet	$2,411.00
9	AO Modulator Set	Isomet	$2,029.00
10	AO Modulator Set	Isomet	$1,555.75
11	High Speed Detector	New Focus	$3,744.66
12	Digital Scope	Fotronil	$2,350.00
13	Lab computer	Superior Computer	$1,432.00
14	Cryostat	Janis	$9,550.01
15	Vacuum Pump	Leybold Vacuum	$2,729.28
16	Laser Tube Magnet	Evergreen	$4,550.48
17	Receiver, Power Supply	New Focus	$1,522.77

18	Chirped Laser System	Custom	$2,122.41
19	optical isolater	Optics for Research	$2,684.00
20	8-Diode Laser Driver	Custom	$1,224.51
21	Laser Frequency Stabilizer	Custom	$5,455.37
22	Laser Tube	Evergreen	$7,900.00
23	100 MHz EO Modulator	New Focus	$3,793.45
24	Laser Mounting System	Kinetic Systems	$3,571.00

Special Circumstances and Changes

The following explains the purpose of the equipment purchased and any special circumstances and changes from the original equipment list. The equipment list differed from the original equipment list, since after the award we found that the Spectra-Physics mode-locked oscillator and regenerative amplifier would not deliver Fourier Transform limited pulses of the appropriate power and duration needed for these investigations. Other avenues were explored. If was found that the Clark Laser system could deliver the pulses needed for the investigations in the 10 to 100 Ghz regime. To explore the 1-10 GHz regime, chirped diode lasers were chosen. To create the data to be processed, an existing modulated cw Ti:Sapphire is used, however stabilization of this laser was needed and equipment was purchased for this purpose. The equipment purchased supported studies in these to bandwidth regimes. The research projects supported by the acquired equipment is explained in the next section.

Originally, the DURIP grant was to fund the regenerative amplifier and the MURI grant was to fund the mode-locked oscillator from Spectra-Physics. Instead, a Clark-MXR picosecond mode-lock/regenerative amplifier system was purchased and the purchase was shared between the grants and cost-sharing. The cost listed in Item 1 is the share paid for out of DURIP funds. Item 2 is Spectra-Physics Millenia Pump laser needed to pump the mode-locked oscillator in Item 1. Item 3 is a solid etalon used to convert the 8 ps Fourier transform limited pulses from Item 1 to 31 ps Fourier transform limited pulses that match the 17GHz processing bandwidth of the processing material used (Tm:YAG). Item 4 and 5 is a power meter and a beam analyzer used to measure and align the picosecond laser system. The power and spatial structure of the laser beams is critical for evaluating the processors efficiency and for spatial crosstalk studies. Item 6 is a spatial filter used to clean up laser beam's spatial profile, which aids in the isolation of the output signal. Item 7 is a variable beamsplitter system used to split beams for crossed-beam experiments, done to spatially separate input and output going beams. Item 8, 9, and 10 are acousto-optic modulators used to modulate input beams and gate output beams. Item 11 is a high speed detector for detecting processed multi-GHz waveforms. Item 12 a digital scope used to record and characterize output signals. Item 13 is the lab computer used for data acquisition and analysis of data. Item 14 and 15 are the cryostat and vacuum pump used to maintain the processing materials under investigation at cryogenic temperatures. Item 16 is a magnet for the laser used to study the spectroscopy of processing materials. Item 17 is a receiver and power supply from New Focus used for slow demonstrations (40Mhz) of true-time delay. Item 18 is a custom-built chirped laser system designed and fabricated at Montana State University capable of programming materials for processing at up to 3 GHz bandwidth. Item 19 is an optical isolater that is needed to isolate the chirped laser from reflections. Item 20 is a custom-built box capable of driving eight diode laser and will be used for multi-beam experiments. Item 21 is a

custom-built external laser frequency stabilizer needed when processing large length codes. Initially the system is being used to lock the Ti:Sapphire laser to a stabilized cavity. It can also be used to lock a laser to a spectral hole burned in an absorption line. Item 22 is a laser tube for stabilized laser system. Item 23 is a 100 MHz EO modulator used to put side-bands on the laser light needed to be stabilized before it is sent to the cavity or absorption line. Item 24 is a laser mounting system for supporting the stabilized Ti:Sapphire.. Item 25 is a Newport Translation Stage, which is part of the frequency stabilization system.

<u>Supported Research Projects</u>

The following are the research projects supported by the acquired equipment.

Photonics for RF Signal Processing: Spatio-temporal Array Processing

This research is carried out as a subaward under the University of Colorado and is supported by the Office of the Secretary of Defense MURI program through the Office of Naval Research (grant number N00014-97-1-1006.

The MURI research brings together a multi-disciplinary team from the University of Colorado (Lead) and Montana State University to investigate the application of photonic techniques to the control and processing of advanced RF systems using novel optical materials and devices. A team is assembled with expertise in algorithms, optical systems, optical physics, nonlinear optics, optical materials, photodetectors, photorefractives, optical coherent transient materials, optical links, and photonically controlled arrays to realize the full benefits of photonic technology applied to RF systems. The extremely demanding problem of control and processing of large, wide-bandwidth phased-array antennas is a central focus of this effort, exploring issues from materials and device fundamentals through algorithms and implementations. Additional efforts investigate novel approaches to IR countermeasures, novel nonlinear optical materials, frequency tunable laser sources and amplifiers, high-saturation-power wide-bandwidth photodetectors, as well as radar imaging and target recognition.

The research conducted at the Montana State University in collaboration with the MURI team at the University of Colorado involves the application of coherent transient technology to true-time delay regenerators and adaptive beamforming at bandwidths of 10 GHz and greater.

Wide-Band Optical True-Time-Delay and Adaptive Beamforming

This research is supported by the Army Research Office as part of the DEPSCOR program (grant number DAAG55-98-1-0244). A sub-award goes to the University of Colorado.

Two key issues in the operation of large broadband antenna arrays are efficient management of the inherent complexity of these systems and efficient implementation of controllable, broadband true-time-delays. Optical coherent transient technology has the capability of efficiently imposing true-time-delays up to several microseconds on signals with bandwidths in excess of 100 GHz. These attributes, combined with the added advantage that 1) these delays are controllably programmable, 2) that over 10^5 delays can be programmed in a cubic centimeter of material, and 3) that phase and amplitude sensitive processing and delay can be performed simultaneously, make coherent transient true-time-delay an extremely promising technology for future radar systems. In order to feasibly utilize coherent transients in large broadband arrays, an architecture is needed that efficiently manages the inherent complexity of controlling such

demanding systems and is compatible with programming multiple delays into coherent transient materials.

This research combines Montana State University's expertise in coherent transient systems and materials with the University of Colorado's extensive expertise in adaptive beamforming using optical techniques. The research under this grant involves a novel phased array processing architecture that utilizes the inherent true-time-delay of optical coherent transients, but also performs the weight multiplication and even the adaptive weight calculation using correlation cancellation loops. This new algorithm makes broadband beamforming extremely efficient and simple to implement in RF photonic hardware. For an *N* element antenna array, the system requires only *N*+2 broadband modulators (electrooptic up to 10 GHz), one high speed detector, and no acoustooptic delay lines are required. Our approach is compatible with real-time calculation of the required number of adaptive weights that encompass the necessary degrees of freedom to beamsteer and null rotate without squint in an arbitrarily complex spatio-temporal signal environment. Our approach could revolutionize the processing of large broadband phased arrays by allowing fully adaptive and optimal performance to be accomplished by a processor whose hardware complexity does not grow with number of array elements as do all other real-time digital or analog phased array processing systems.

The objective of our research effort is to demonstrate an optical coherent transient based adaptive beamforming architecture capable of operating on signals with bandwidths well in excess of a gigahertz. We are first modeling and analyzing our architecture while at the same time pushing coherent transient true-time-delay technology from its current demonstration bandwidth of several megahertz to the required bandwidth of several gigahertz. We will then implement our refined architecture at low bandwidths, utilizing our expertise in and existing infrastructure for development of optical adaptive beamforming system. Relying on the lessons learned from these efforts, we will demonstrate multi-gigahertz bandwidth adaptive beamforming.

Advanced Coherent Transient Systems and Devices

This research is supported by the Air Force Office of Scientific Research (grant number F49620-98-1-0283). A sub-award goes to the University of Washington.

Real-time, wide band information storage and signal processing devices are critical to many military and commercial systems. Optical coherent transient technology has the potential to perform real-time storage and continuous signal processing at data rates up to a terahertz, with storage/pattern densities on the order of a terabit per centimeter squared, and with data block sizes/time-bandwidth products well over 10000. These attributes, coupled with spatial selectivity and the ability to process amplitude, phase, and frequency-modulated signals makes coherent transients an extremely versatile technology. Previously proposed applications include target and pattern recognition; multi-dimensional cache memory; high density, high bandwidth database memory, associative memory, and look-up tables; secure communications; interior memory for optical networks; real-time address decoder; all optical passive routing of data; header stripper/isolator for network packets; and dynamic pulse shaping and distortion compensation.

Under this grant, we are looking beyond the traditional implementations and applications of coherent transients and exploring novel concepts that exploit the processing and non-linear behaviors of coherent transient systems. These area include 1) true-time delay regenerators, 2) continuously programmed continuous processor, 3) feedback and learning, 4) efficient writing and reading of spatial-spectral gratings, 5) inversion and gain gratings, 6) index modulation, 7) single sideband and frequency modulation, and 8) bilinear transforms and circuit modeling. The proposed research also explores critical issues that significantly impact the development of practical coherent transient systems. These include: 1) orthogonal code development and testing

2) modeling and characterization of gated systems, 3) non-linear time shifts, and 4) cryocooler evaluation.